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# Strength and Durability of Glass Fiber Composites Treated With Multicomponent Sizing Formulations

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# Strength and Durability of Glass Fiber Composites Treated With Multicomponent Sizing Formulations

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# Abstract

Commercial fiber-sizing packages have been developed to enhance the strength and moisture resistance of composite materials, which typically decreases ballistic performance. Potential sizing packages developed for Future Combat Systems will need to enhance ballistic response while maintaining the levels of durability currently benchmarked by existing commercial systems. For this research, pultruded vinyl ester/E-glass composites were manufactured in which the silane, film former resin, and surfactant reactivity were varied to mimic the complete spectrum of commercially available fiber-sizing packages. The interlaminar shear strengths of dry and moisture-saturated composites were then measured via 3-point bend testing. These strength and durability results will be used as the standards of comparison for future development of ballistic sizing packages for composite armor applications.

# Acknowledgments

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# 1. Introduction

The fatigue life, vibration response, structural loading, moisture resistance, and most importantly, the ballistic resistance of the structural composite layer found in composite integral armor (CIA) will be dependent upon the chemical and physical properties of the fiber-matrix interphase [1]. The interphase is the small region of material surrounding the fiber that has properties that differ from the fiber and the bulk matrix [2]. The response of the fiber-matrix interphase, which may only compose as little as 1% of the total volume of material, can control the overall mechanical performance (strength, durability, fatigue life) as well as micromechanical energy absorbing mechanisms of glass fiber-reinforced composite materials [3–6]. During a ballistic event, a significant portion of the incident energy during dynamic loading of the polymeric composites may be absorbed through micromechanical mechanisms such as fiber-matrix debonding and fiber pull-out, which are directly related to the properties of the interphase [7]. Understanding the individual contribution of each mechanism is key to tailoring the interphase to achieve maximum energy absorption.

The driving force for the formation of an interphase in glass fiber-reinforced composites is the use of waterborne silane-based sizing packages. The sizing package increases the handling ease of the glass fibers while lending protection against damage and corrosion [8, 9]. The sizing package is applied from an aqueous emulsion with the solids content mainly composed of polymeric film former (70% by weight). Other minor components of the sizing package include surfactant, thickeners, antifoam agents, antistatic agents, stabilizers, and a silane-based coupling agent. Although the silane coupling agent makes up a relatively low percentage of the initial sizing package, it serves the critical purpose of providing a chemical covalent link between the matrix phase and fiber. The silane coupling agent is first hydrolyzed in the aqueous sizing emulsion. Upon drying on the fiber surface, the hydrolyzed silanes condense and react with silanol groups found on the fiber surface to form a loosely crosslinked siloxane network. Once contact has been made between the fibers and the matrix resin, the relative proportions of the sizing components on the fiber surface change dramatically as diffusion between the matrix resin and fiber sizing occurs. At equilibrium, the matrix resin dissolves most of the film former and surfactant, leaving a high concentration of crosslinked siloxane at the glass surface (80% by weight) [7]. The matrix resin then diffuses into and swells the loosely crosslinked siloxane network, which remains chemically bonded to the glass surface. Chemical bonding occurs during cure between the matrix resin and matrix-resin-compatible functional groups of the pre-existing siloxane network to form a highly crosslinked and coupled interpenetrating polymer

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network (IPN) structure. This IPN structure has properties that differ from the fiber and bulk matrix phase, hence the term "interphase."

The Future Combat Systems (FCS) will require unique materials solutions to meet the weight, speed, and performance requirements envisioned for the objective force. Integrated multimaterial assemblies that incorporate fiber-reinforced composite materials are candidates to meet both structural and ballistic requirements for envisioned lightweight Army ground vehicle applications. The anticipated material property requirements for FCS will require substantial increases in composite materials performance for these unprecedented applications. Unfortunately, while many commercial fiber-sizing packages offer excellent durability properties, the ballistic impact resistance of such composites is less than ideal. A great challenge will be the simultaneous improvement in both composite ballistic response and structural load bearing, since these performance attributes are generally diametrically opposed. Potential sizing packages developed for FCS will need to enhance ballistic response while maintaining the levels of durability currently benchmarked by existing commercial systems. For this research, pultruded vinyl ester/E-glass composites were manufactured in which the silane, film former resin, and surfactant reactivity were varied to mimic the complete spectrum of commercially available fiber-sizing packages. The interlaminar shear strengths of dry and moisture-saturated composites were then measured via 3-point bend testing. These strength and durability results will be used as the standards of comparison for future development of ballistic sizing packages for composite integral armor applications.

## 2. Experimental

### 2.1 Fiber Tow Preparation

E-glass fiber tow, prepared by Gorowara et al. [10] at the Owens Corning Science and Technology Center pilot plant facility in Granville, OH, was used to construct cylindrical pultruded rod composite samples. The silane-based fiber-sizing packages were applied from a waterborne emulsion (5.0 wt% solids) to the E-glass fibers immediately after drawing the glass fibers from the melt. The aqueous fiber-sizing package is composed of 0.6 wt% percent silane coupling agent and 4.4 wt% emulsified film former. Fiber-sizing packages were prepared with a variety of silane coupling agents including methacrylpropyltrimethoxysilane (MPS), aminopropyltriethoxysilane (APS), and glycidoxypropyltrimethoxysilane (GPS). The MPS, APS, and GPS were obtained from Witco OSi (A-1100, A-174, and A-187, respectively). The chemical structures of the silane coupling agents are portrayed in Figure 1. The film former resins chosen included diglycidyl ether of

bisphenol A (DGEBA) epoxies of varying epoxy equivalent weight (Shell EPON 828, 834, and 1001F), unsaturated bisphenol A vinyl ester (Sartomer CN-151), and polyesters (Reichold Atlac 387 and DSM Neoxil 954D). The film former resins used are illustrated in Figure 2. The hydrophobic film former resins were stabilized in an emulsified form using a nonionic polyethylene oxide-polypropylene oxide-polyethylene oxide triblock copolymer surfactant (BASF Pluronic F-108). The chemical structure of the surfactant used to emulsify the sizing packages is illustrated in Figure 3. The fibers were dried for a period of 10 hr at a temperature of 130 °C prior to shipping to the U.S. Army Research Laboratory (ARL). The tows had an average 1150 mg/m tex, 2052 filaments/tow, and an average 16.9-μm filament diameter.
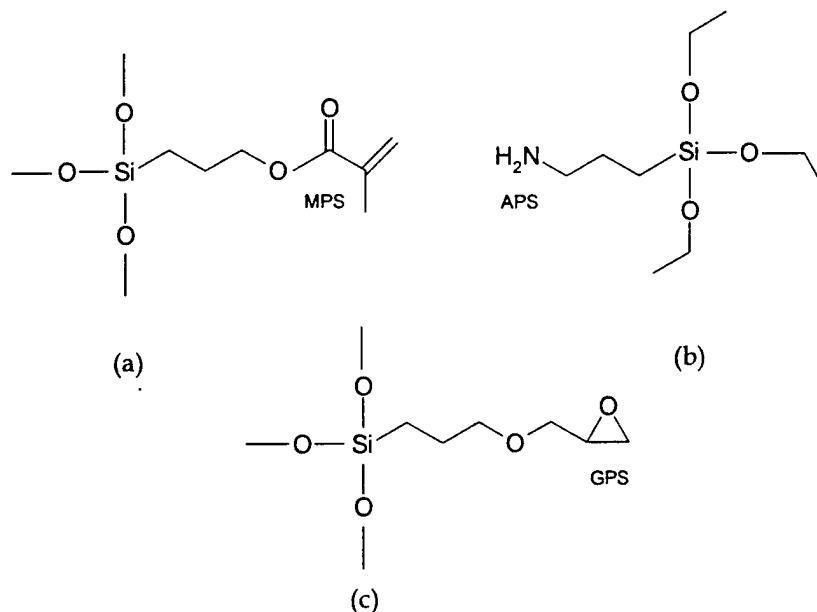


Figure 1. Molecular structures of (a) MPS, (b) APS, and (c) GPS.

## 2.2 Matrix Resin

For a single pultruded rod composite, ~200 g of vinyl ester resin was prepared. In circumstances where fiber wetting was difficult, specifically for the cases of noncompatible fiber-sizing packages, 250–300 g of resin were used. The formulation was composed of Derakane 411-C-50 vinyl ester resin (Dow) and 1.7 wt% Trigonox 239A peroxide initiator. Because the rods are cured at room temperature (20–25 °C), 0.10 wt% cobalt napthenate was added as a room temperature catalyst. Cure and crosslinking occur via a free radical mechanism. The matrix vinyl ester resin and styrene reactive diluent are illustrated in Figure 4.

EPON 834 DGEBA Epoxy

CN-151 DGEBA Epoxy Methacrylate

NEOXIL 954-D DGEBA Unsaturated Polyester, MW ~ 5500
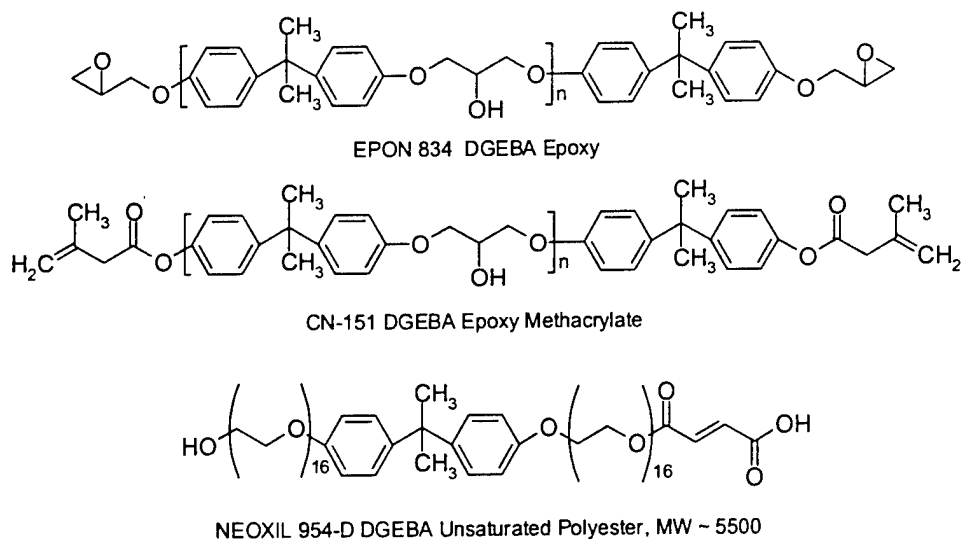
Figure 2. Film former resins used in the fiber-sizing packages.

$$HO\text{---}(CH_2CH_2O)_x\text{*---}(CH_2\overset{CH_3}{\underset{}{C}}HO)_y\text{*---}(CH_2CH_2O)_x\text{---}H$$
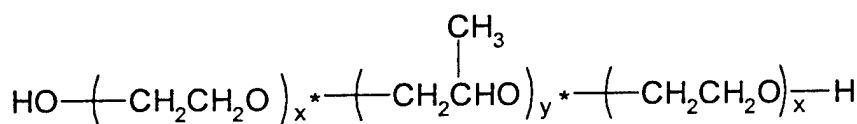
Figure 3. BASF Pluronic F-108.

vinyl ester resin derived from bisphenol A
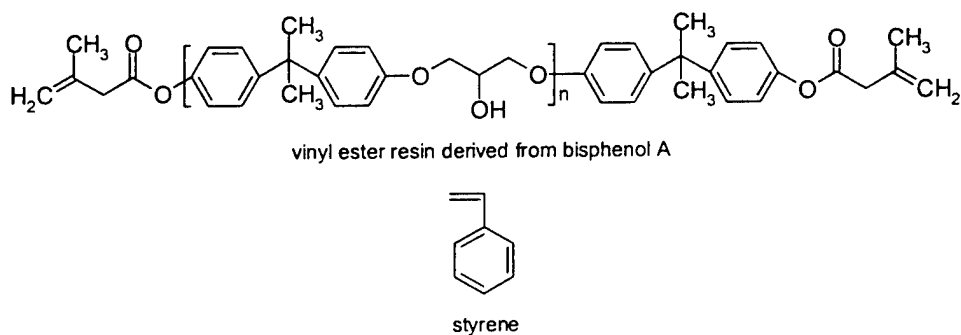
styrene

Figure 4. Vinyl ester matrix and styrene reactive diluent.

## 2.3 Cylindrical Pultruded Composite Rod Fabrication Equipment

The basic apparatus for pultruded rod synthesis consisted of three main components: (1) an area for wetting the fiber tows (fiber trough), (2) polytetrafluoroethylene (PTFE)-lined copper pipe molds, and (3) a frame for the suspension of the resin-filled rod molds during room temperature curing. Figure 5 shows the schematic diagram of the mold assembly used to fabricate the pultruded composite rods.

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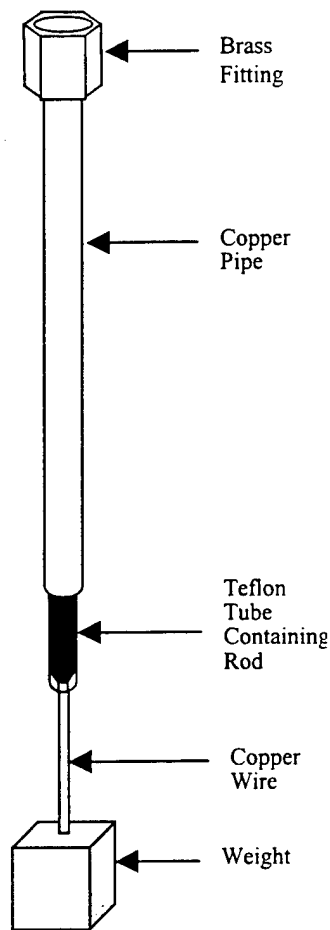
Figure 5. Pultruded composite rod fabrication setup.

The PTFE tube was utilized within the copper pipe to reduce adhesion of the matrix vinyl ester resin to the inner surface of the copper pipe upon completion of cure. A brass fitting was then attached to the pipe with a set of Swagelok fittings. After the wetted fibers are pulled through the PTFE tube-copper pipe setup, a plastic "zip-tie" was used to firmly secure the fibers in the brass fitting. Another function of the brass fitting was to serve as a "resin reservoir," which facilitated further wetting of the fibers using excess resin poured into the fitting. Finally, the PTFE tube-copper pipe setup was suspended from a frame via the Swagelok fitting, and a weight of approximately 5 kg was firmly secured to the copper wire that protruded from the bottom of the mold. The weight effectively placed enough tensile force on the fibers to ensure unidirectional alignment in the final composite specimens.

## 2.4 Cylindrical Pultruded Composite Rod Fabrication Procedure

The complete process of creating the composite rods begins with the careful spinning of the fibers into a bundle of 38 tows. The exact number of tows ($J$) needed to produce a composite rod with a fiber volume fraction of $\phi_f = 0.50$ can be calculated using the following equation:

$$J = \frac{D_t^2 \cdot \phi_f}{2N \cdot d_f^2} \times 10^6 \, , \tag{1}$$

where

$N$ = the number of filaments per tow,

$D_t$ = the PTFE inner-tube diameter in millimeters, and

$d_f$ = the fiber diameter in microns.

The fiber spinning was completed using a plastic loop frame. Care was taken to ensure that the fiber tows were reasonably aligned and taut during this step. The diameter of the loop also had to be slightly longer than twice the mold length. A wetting trough was then used in collaboration with a laminate hand roller and the resin to effectively wet out the fibers inside a fume hood. The wetting trough needed to be as long as the diameter of the bundle loop and also needed be lined with a release sheet to facilitate clean-up. Careful rolling was required to ensure that the fibers did not fray or that the resin did not gel or begin to cure. This process typically spanned 10–15 min. A copper wire was looped around the middle of the fiber bundle, and the copper pipe was flipped upside-down so that the brass fitting was directly above the wetted fiber bundle. A second individual was needed to pull the fiber bundle through the copper pipe. One person pulled the copper wire with the fibers through the tube, while the second person secured the copper tube and PTFE tube combination. When approximately 1 in of fibers was left protruding from the brass fitting, a zip-tie was used to secure the fibers in the brass fitting. The copper pipe-PTFE tube combination was again flipped over and hung on the support frame. A small amount of resin, ~20 g, was deposited into the top of the brass fitting, and the 5-kg weight was secured to the copper wire as shown in Figure 5. Finally, the composite rod was allowed to cure at room temperature for ~2 hr in an enclosed fume hood. Once the composite rods had completely cured inside the fume hood, the 5-kg weight was removed, and the complete copper pipe-composite rod combination was placed in an oven at 110 °C for 1 hr. The oven was then shut off and the composite rods were allowed to slow cool to minimize internal residual stresses.

## 2.5 Composite Rod Test Sample Preparation

The composite rod was carefully removed from the PTFE tube and copper pipe. A hacksaw was then used to detach the rod from the brass fitting and copper wire. Upon removal, the rod was inspected for defects and placed in a desiccator to ensure dryness. Before testing, the rod was carefully sawed into pieces 2.375 in long. (A diamond saw or other precise cutting instrument is strongly recommended to complete this task.) The ends of the cut rods were lightly sanded with 400-grit sandpaper and replaced in the desiccator in labeled sample bags until further testing. All rods were dried in a vacuum oven at 50 °C and –25-in mercury (Hg) overnight before any testing was begun.

## 2.6 Density Measurements

Density measurements were made using a balance from which a pan was submerged into a beaker filled with distilled water. Figure 6 displays a schematic of the instrument used to measure the density of the composite rods.
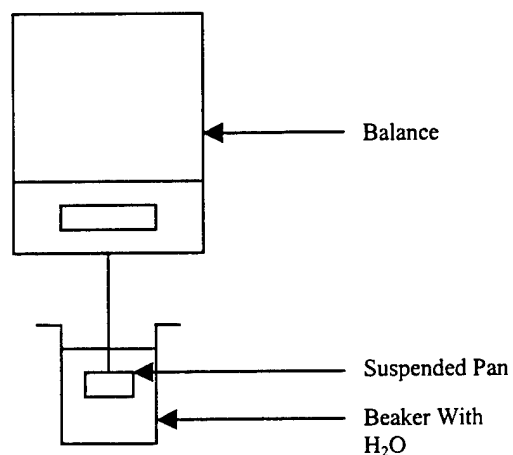


Figure 6. Specific gravity measurement apparatus.

The distilled water was allowed to equilibrate overnight to room temperature. The procedure required three measurements, including the dry mass of each rod, the mass of the pan submerged in the water, and the mass of the rod resting on the pan submerged in water. The following formula was used to calculated the specific gravity of each rod ($SG_{rod}$):

$$SG_{rod} = \frac{A}{A + W - B} , \qquad (2)$$

where

$A$ = the dry mass of the rod,

$B$ = the mass of the submerged rod and pan, and

$W$ = the mass of the submerged pan only.

Density ($D_c$) is then calculated from equation (3):

$$D_c = SG_{rod}(T) \times \rho_{H_2O}(T) \, , \tag{3}$$

where

$T$ = the test temperature and

$\rho_{H_2O}(T)$ = the density of water at the tested temperature.


## 2.7 Short Beam Shear Testing

The Instron 1331 equipped with a 2000-lb load cell was used in collaboration with a set of custom-made American Society for Testing and Materials (ASTM) D4475-85 [11] standard steel fittings. The setup including the fittings is depicted in Figure 7. Before testing, the diameter of each specimen was measured to the nearest 0.001 in at the midpoint. The rod was placed in the test fixture as shown in Figure 7. The specimen was then aligned so that the midpoint was centered and the long axis was perpendicular to the loading nose. The bottom fittings were then adjusted to a span of 2.45 in. A computer was utilized in collaboration with the Instron 1331 to collect load force and displacement data. The load was applied to the specimen at a crosshead speed of 1.3 mm/min. Testing was declared completed when the specimen exhibited stress fractures indicated by a sudden, rather large, decrease in load-force readings on the Instron 1331 instrument control panel. Four trials of each specimen were made. Interlaminar shear strength ($ILSS$) was calculated using equation (4):

$$ILSS = \frac{0.849 \times P}{(D_{rod})^2} \, , \tag{4}$$

where

$P$ = the maximum measured load and

$D_{rod}$ = the rod diameter.

Additionally, samples were also tested after reaching an equilibrium moisture uptake percentage ($M_\infty$) upon exposure to water at a temperature of 50 °C. Composite durability is then defined simply as the ratio of wet ILSS to dry ILSS.

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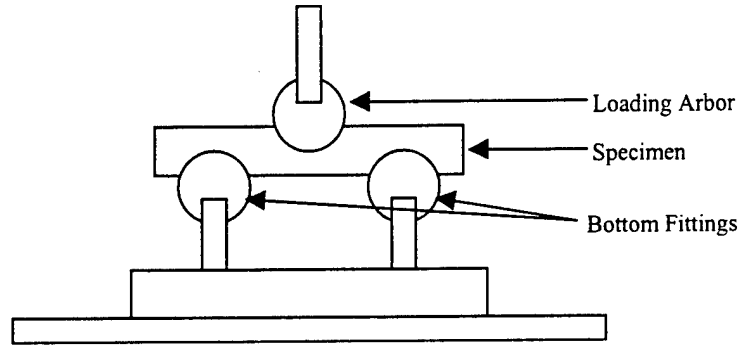
Figure 7. ASTM short beam shear test fittings.

## 2.8 Void Content Testing

The samples used for short beam shear testing were re-used for void content testing after drying in the vacuum overnight at 50 °C and –25-in Hg. All samples were weighed completely dry. Then, the crucibles, in which the samples were placed, were massed. The samples were heated at 1100 °F for approximately 3 hr to burn off the vinyl ester matrix, leaving clean E-glass fibers behind. The crucibles and the clean E-glass fibers that they contained were massed. By subtracting the weight of the crucible, the actual E-glass fiber mass was calculated. From these measurements, the E-glass fiber mass percent ($X_f$) and the matrix mass percent ($X_m$) were calculated using the following equations:

$$X_f = \frac{F}{M} \times 100\% , \tag{5}$$

and

$$X_m = 100\% - X_f , \tag{6}$$

where

$F$ = the E-glass fiber mass and

$M$ = the sample dry mass.

From these computations, the void content ($\phi_v$) and the volume fraction of the fibers ($\phi_f$) were easily calculated from:

$$\phi_v = 100 - D_c (\frac{X_m}{D_m} + \frac{X_f}{D_f}) , \tag{7}$$

and

$$\phi_f = D_c (\frac{X_f}{D_f}) , \tag{8}$$

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where

$D_c$ = the specimen density,

$D_m$ = the matrix density (1.130 g/cm³), and

$D_f$ = the fiber density (2.600 g/cm³).

## 2.9 Dynamic Mechanical Analysis

Dynamic mechanical analysis (DMA) was carried out using a TA Instruments 2980 DMA in the dual cantilever-bending mode. The neat vinyl ester resin was tested using a 20-mm clamp frame and oscillatory displacement amplitude of 7.5 µm. The displacement amplitude was verified to ensure linear viscoelastic response by deriving corresponding stress-strain ($\sigma$-$\varepsilon$) curves. Constant heating rate experiments were carried out at 2.0 °C/min at a frequency of 1 Hz from 35° to 200 °C. The glass transition temperature ($T_g$) was taken as the peak maximum of the loss modulus ($E''$) curve measured at 1 Hz.

# 3. Results

The loss modulus ($E''$) and storage modulus ($E'$) DMA results for the neat non-fiber-reinforced vinyl ester matrix are shown in Figure 8. The $E''$ curve shows a small relaxation peak near 80 °C and a large glass-to-rubber transition peak at approximately $T_g$ = 125 °C. The storage modulus also decreases from glassy values in excess of $10^9$ Pascals (Pa) below temperatures of 110 °C to rubbery values of $10^7$ Pa above temperatures of 145 °C. The rubbery plateau at temperatures greater than 145 °C is typical for crosslinked thermosets. The small relaxation peak near 80 °C could be the result of heterogeneous regions of crosslink density within the cured vinyl ester sample [12]. However, the purpose of performing DMA was not to investigate the molecular relaxation mechanisms of cured and crosslinked vinyl ester resin in detail, but rather to simply verify that the curing procedure and conditions resulted in glassy crosslinked thermoset for the moisture uptake and mechanical property measurements.

The ILSS (wet and dry), moisture uptake percentages, and durability results are plotted in Figures 9–14. These results are numerically tabulated in Tables 1–3 along with the specimen weight fraction of fibers, void content percentage, and moisture uptake percentage.
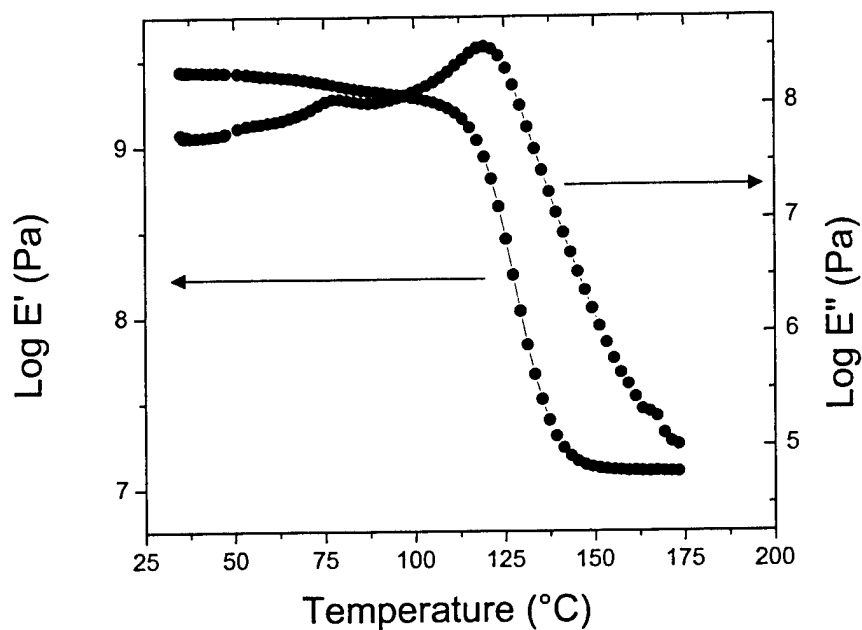
Figure 8. DMA of the vinyl ester matrix showing a glass transition temperature of approximately 125 °C.
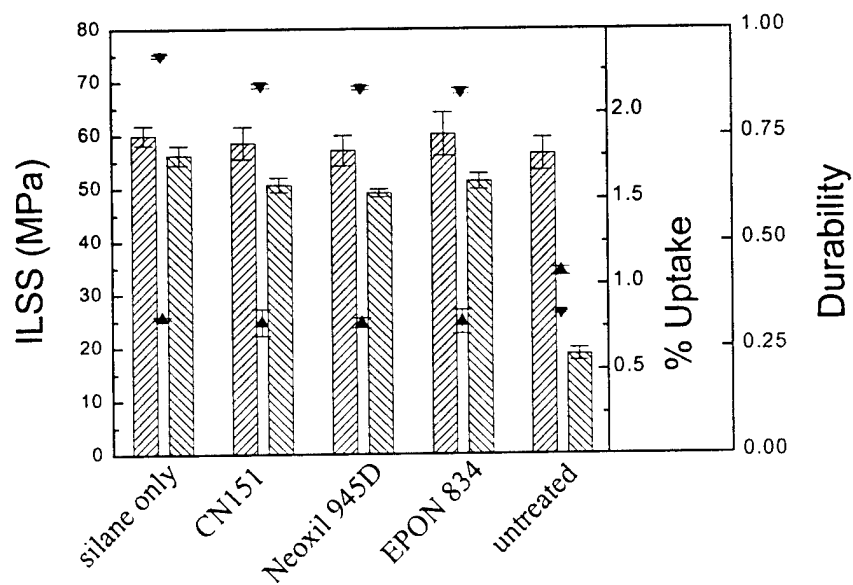


Figure 9. ILSS (dry = left bar, wet = right bar, for given film former), equilibrium moisture uptake percentage at 50 °C (percent uptake = up triangles), and durability (ratio of wet ILSS to dry ILSS = down triangles) for pultruded rod composites with MPS coupling agent and varying film former reactivity towards the matrix vinyl ester resin.
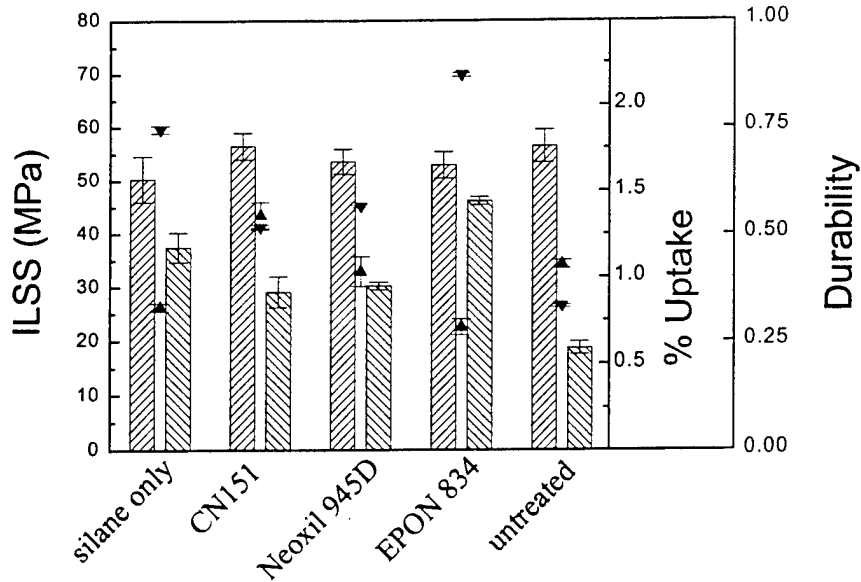
Figure 10. ILSS (dry = left bar, wet = right bar, for given film former), equilibrium moisture uptake percentage at 50 °C (percent uptake = up triangles), and durability (ratio of wet ILSS to dry ILSS = down triangles) for pultruded rod composites with APS coupling agent and varying film former reactivity towards the matrix vinyl ester resin.
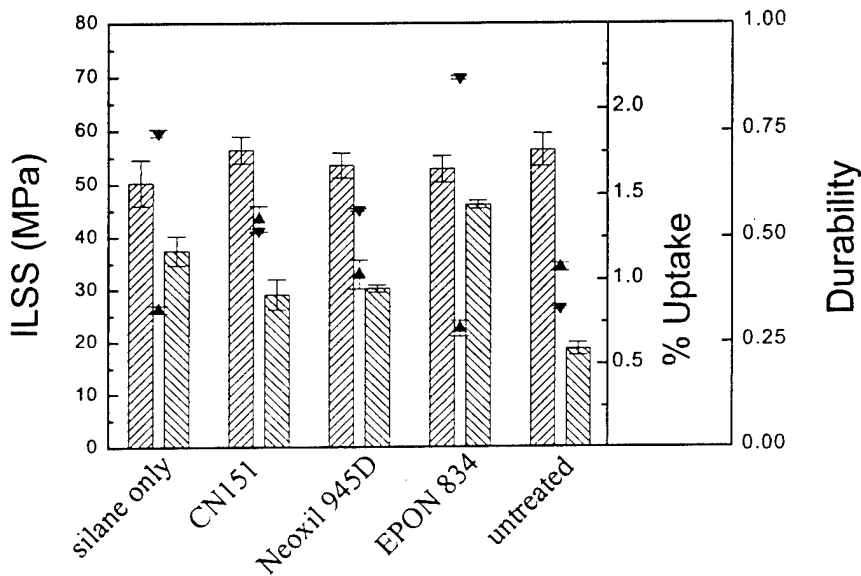


Figure 11. ILSS (dry = left bar, wet = right bar, for given film former), equilibrium moisture uptake percentage at 50 °C (percent uptake = up triangles), and durability (ratio of wet ILSS to dry ILSS = down triangles) for pultruded rod composites with GPS coupling agent and varying film former reactivity towards the matrix vinyl ester resin.

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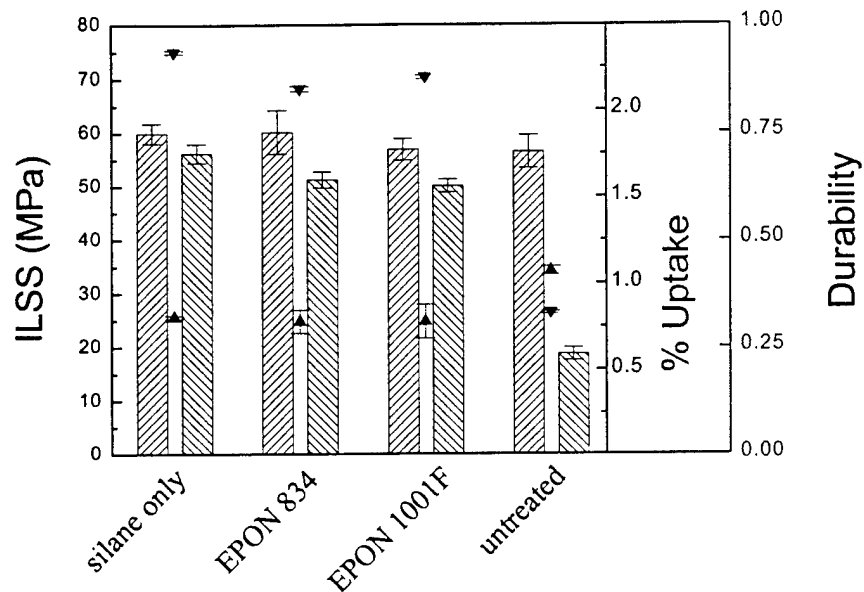
Figure 12. ILSS (dry = left bar, wet = right bar, for given film former), equilibrium moisture uptake percentage at 50 °C (percent uptake = up triangles), and durability (ratio of wet ILSS to dry ILSS = down triangles) for pultruded rod composites with MPS coupling agent and varying film former molecular weights.
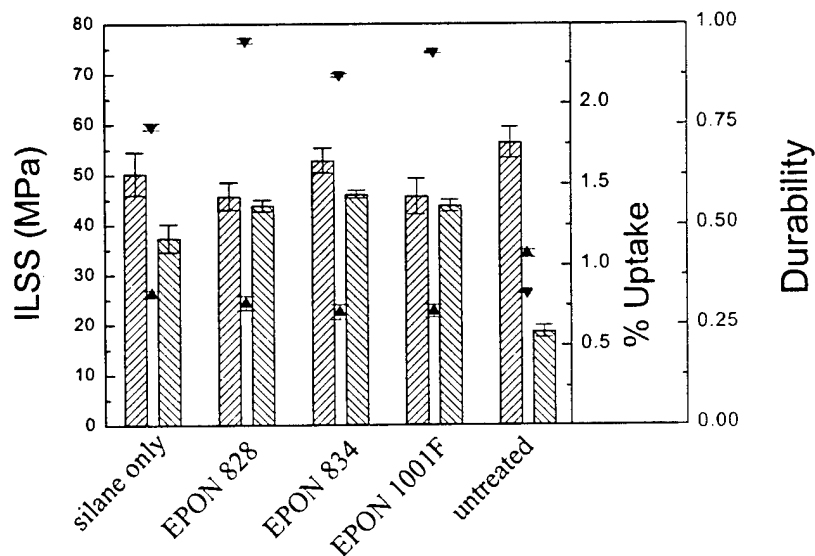


Figure 13. ILSS (dry = left bar, wet = right bar, for given film former), equilibrium moisture uptake percentage at 50 °C (percent uptake = up triangles), and durability (ratio of wet ILSS to dry ILSS = down triangles) for pultruded rod composites with APS coupling agent and varying film former molecular weights.
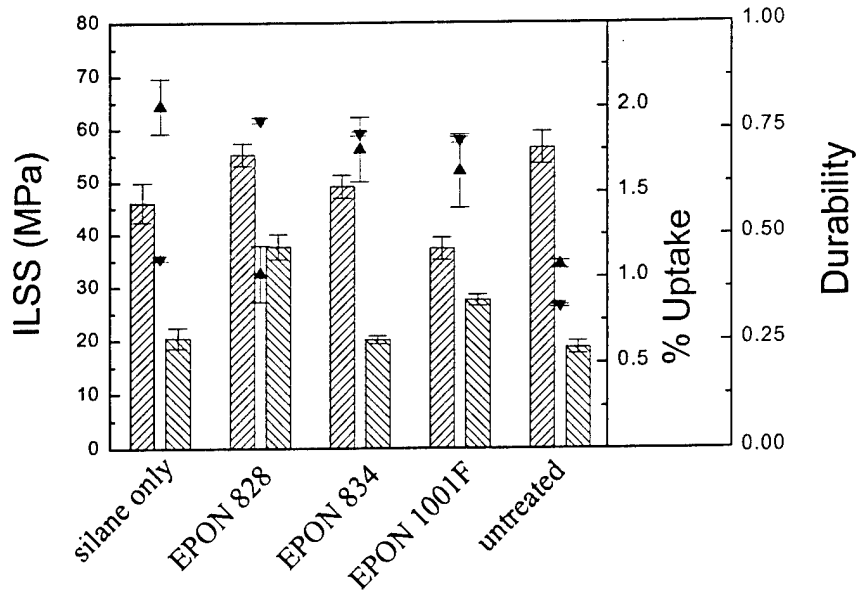
Figure 14. ILSS (dry = left bar, wet = right bar, for given film former), equilibrium moisture uptake percentage at 50 °C (percent uptake = up triangles), and durability (ratio of wet ILSS to dry ILSS = down triangles) for pultruded rod composites with GPS coupling agent and varying film former molecular weights.

Table 1. Complete summary of results for vinyl ester pultruded glass rod composites with MPS as the coupling agent.

| Film Former | $X_f$ | $\phi_v$ (%) | $D_c$ (g/cm³) | Dry ILSS (MPa) | $M_\infty$ (%) | Wet ILSS (MPa) | Durability |
|---|---|---|---|---|---|---|---|
| Silane Only | 0.6980 ± 0.0106 | 0.9741 ± 0.0096 | 1.8184 ± 0.0049 | 59.943 ± 1.834 | 0.8039 ± 0.0085 | 56.205 ± 1.783 | 0.9376 ± 0.0041 |
| EPON 834 | 0.6805 ± 0.0013 | 0.9882 ± 0.0012 | 1.8150 ± 0.0030 | 60.154 ± 4.055 | 0.7791 ± 0.0681 | 51.290 ± 1.468 | 0.8527 ± 0.0062 |
| EPON 1001F | 0.6671 ± 0.0059 | 0.9977 ± 0.0053 | 1.8100 ± 0.0130 | 56.895 ± 2.036 | 0.7783 ± 0.0975 | 50.033 ± 1.221 | 0.8794 ± 0.0038 |
| CN 151 | 0.6823 ± 0.0033 | 0.9899 ± 0.0031 | 1.8211 ± 0.0117 | 57.044 ± 3.457 | 0.7781 ± 0.0724 | 53.810 ± 1.535 | 0.9434 ± 0.0069 |
| Neoxil 945/D | 0.6853 ± 0.0003 | 0.9852 ± 0.0003 | 1.8175 ± 0.0020 | 57.083 ± 2.849 | 0.7741 ± 0.0279 | 49.138 ± 0.706 | 0.8608 ± 0.0045 |
| Atlac 387 | 0.6839 ± 0.0004 | 0.9851 ± 0.0004 | 1.8148 ± 0.0031 | 52.200 ± 2.947 | 0.8801 ± 0.1117 | 42.783 ± 1.800 | 0.8196 ± 0.0058 |
| No Sizing | 0.7034 ± 0.0058 | 0.9953 ± 0.0054 | 1.8673 ± 0.0035 | 56.436 ± 3.077 | 1.0722 ± 0.0240 | 18.654 ± 1.192 | 0.3305 ± 0.0028 |

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Table 2. Complete summary of results for vinyl ester pultruded glass rod composites with APS as the coupling agent.

| Film Former | $X_f$ | $\phi_v$ (%) | $D_c$ (g/cm³) | Dry ILSS (MPa) | $M_\infty$ (%) | Wet ILSS (MPa) | Durability |
|---|---|---|---|---|---|---|---|
| Silane Only | 0.6495 ± 0.0024 | 1.0068 ± 0.0022 | 1.7978 ± 0.0123 | 50.252 ± 4.288 | 0.8237 ± 0.0221 | 37.449 ± 2.782 | 0.7452 ± 0.0084 |
| EPON 828 | 0.6748 ± 0.0024 | 0.9893 ± 0.0021 | 1.8075 ± 0.0056 | 45.790 ± 2.737 | 0.7665 ± 0.0445 | 43.897 ± 1.130 | 0.9587 ± 0.0062 |
| EPON 834 | 0.6954 ± 0.0083 | 1.0005 ± 0.0077 | 1.8631 ± 0.0049 | 52.871 ± 2.477 | 0.7094 ± 0.0468 | 46.162 ± 0.748 | 0.8731 ± 0.0043 |
| EPON 1001F | 0.6726 ± 0.0044 | 0.9959 ± 0.0040 | 1.8159 ± 0.0049 | 45.738 ± 3.575 | 0.7144 ± 0.0395 | 43.845 ± 1.181 | 0.9586 ± 0.0025 |
| CN 151 | 0.6704 ± 0.0022 | 0.9855 ± 0.0019 | 1.7933 ± 0.0020 | 57.681 ± 3.210 | 1.3576 ± 0.0755 | 29.086 ± 2.902 | 0.5043 ± 0.0056 |
| Neoxil 945/D | 0.6748 ± 0.0028 | 0.9900 ± 0.0025 | 1.8088 ± 0.0014 | 53.545 ± 2.315 | 1.0307 ± 0.0858 | 30.242 ± 0.662 | 0.5648 ± 0.0027 |
| No Sizing | 0.7034 ± 0.0058 | 0.9953 ± 0.0054 | 1.8673 ± 0.0035 | 56.436 ± 3.077 | 1.0722 ± 0.0240 | 18.654 ± 1.192 | 0.3305 ± 0.0028 |

Table 3. Complete summary of results for vinyl ester pultruded glass rod composites with GPS as the coupling agent.

| Film Former | $X_f$ | $\phi_v$ (%) | $D_c$ (g/cm³) | Dry ILSS (MPa) | $M_\infty$ (%) | Wet ILSS (MPa) | Durability |
|---|---|---|---|---|---|---|---|
| Silane Only | 0.6770 ± 0.0032 | 0.9822 ± 0.0029 | 1.7982 ± 0.0020 | 46.159 ± 3.762 | 2.0059 ± 0.1603 | 20.435 ± 1.956 | 0.4427 ± 0.0056 |
| EPON 828 | 0.6989 ± 0.0031 | 0.9926 ± 0.0029 | 1.8544 ± 0.0038 | 42.231 ± 2.722 | 1.0182 ± 0.1653 | 33.534 ± 2.616 | 0.7941 ± 0.0063 |
| EPON 834 | 0.6731 ± 0.0009 | 0.9795 ± 0.0008 | 1.7869 ± 0.0027 | 37.507 ± 1.890 | 1.7511 ± 0.1885 | 27.558 ± 1.047 | 0.7347 ± 0.0050 |
| EPON 1001F | 0.6759 ± 0.0009 | 0.9795 ± 0.0008 | 1.7915 ± 0.0034 | 33.818 ± 2.476 | 1.6228 ± 0.2162 | 24.474 ± 1.574 | 0.7237 ± 0.0071 |
| CN 151 | 0.6840 ± 0.0006 | 0.9917 ± 0.0006 | 1.8271 ± 0.0035 | 55.221 ± 2.153 | 1.1471 ± 0.1707 | 37.661 ± 2.398 | 0.6820 ± 0.0051 |
| Neoxil 945/D | 0.6734 ± 0.0009 | 0.9881 ± 0.0008 | 1.8030 ± 0.0020 | 49.182 ± 2.173 | 1.4229 ± 0.1225 | 20.097 ± 0.739 | 0.4086 ± 0.0023 |
| No Sizing | 0.7034 ± 0.0058 | 0.9953 ± 0.0054 | 1.8673 ± 0.0035 | 56.436 ± 3.077 | 1.0722 ± 0.0240 | 18.654 ± 1.192 | 0.3305 ± 0.0028 |

# 4. Conclusions

The results presented in this report show the influence of the silane coupling agent reactivity, film former reactivity, and film former molecular weight of waterborne glass sizing packages towards the strength and durability of composite materials. The most important conclusion to be drawn from these results is that the greatest overall strength and durability/moisture resistance is obtained when both the silane coupling agent and film former have chemical reactivity with the matrix resin. Of these two sizing components, the degree of silane coupling agent reactivity with the matrix resin phase is the most critical. The order of silane reactivity towards the vinyl ester matrix used in this report is MPS > APS > GPS. The results shown in this report represent the strength and durability benchmarks for ballistic fiber sizing packages to be developed in the future.

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Commercial fiber-sizing packages have been developed to enhance the strength and moisture resistance of composite materials, which typically decreases ballistic performance. Potential sizing packages developed for Future Combat Systems will need to enhance ballistic response while maintaining the levels of durability currently benchmarked by existing commercial systems. For this research, pultruded vinyl ester/E-glass composites were manufactured in which the silane, film former resin, and surfactant reactivity were varied to mimic the complete spectrum of commercially available fiber-sizing packages. The interlaminar shear strengths of dry and moisture-saturated composites were then measured via 3-point bend testing. These strength and durability results will be used as the standards of comparison for future development of ballistic sizing packages for composite armor applications.

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